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SPACE SYSTEMS

STUDY OF APPLICATION OF REMOTE MANIPULATION TO SATELLITE MAINTENANCE

Contract NAS 2-5072
NASA Report No. CR-73-338
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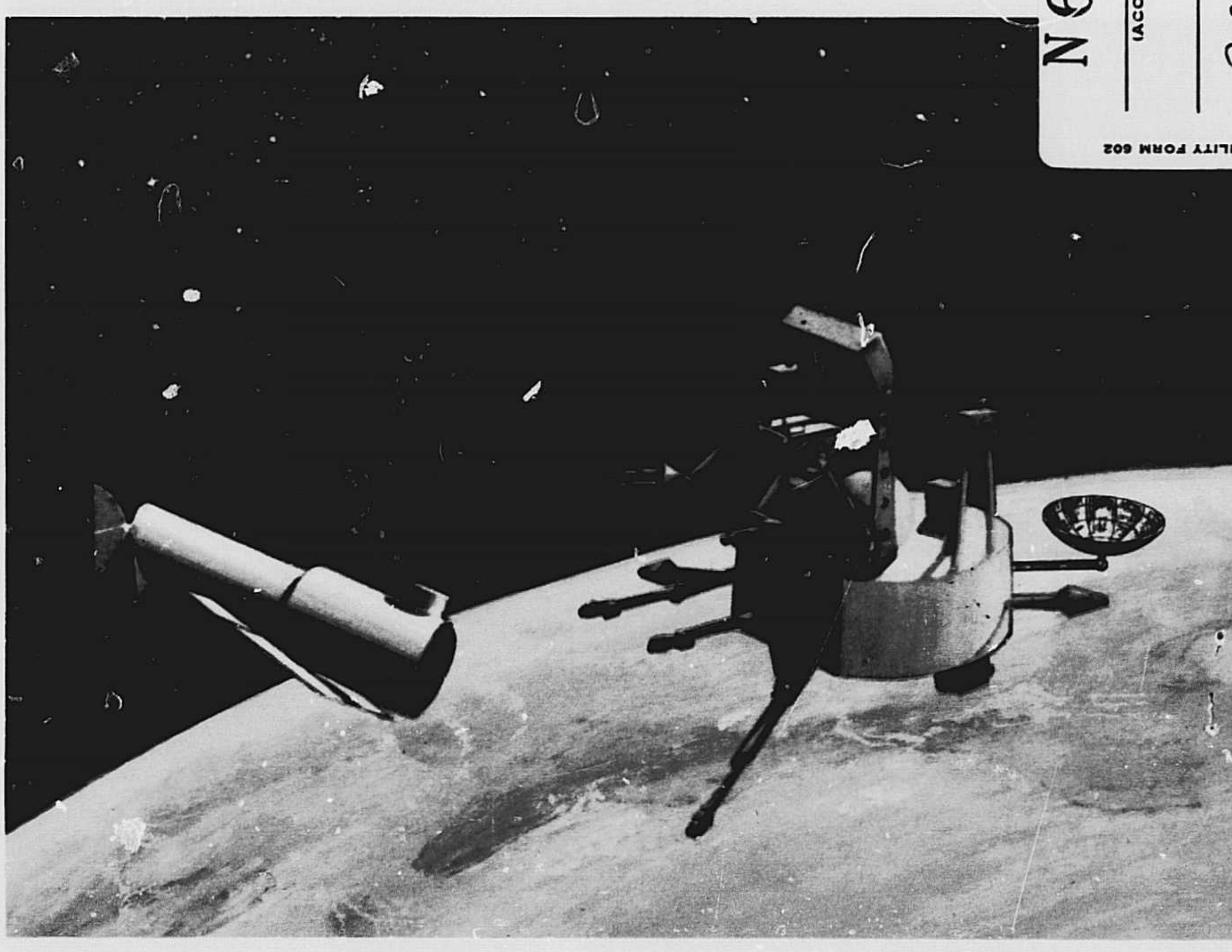

FINAL REPORT Volume I : Summary Report

GENERAL ELECTRIC

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A STUDY OF APPLICATION OF REMOTE MANIPULATION TO SATELLITE MAINTENANCE

Final Report

Volume I : Summary Report

Contract No. NAS 2-5072
NASA Report No. R-73-338

Prepared for

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SECTION 1
INTRODUCTION

Scientists and engineers have devoted a great deal of effort in developing methods for achieving long life and high probability of success in satellite system programs. Design redundancy and extensive testing have been the most widely used techniques. Despite the relatively good success attained through these techniques, occasional catastrophic failures have continued to occur, most often in the more complex systems. Increased probability of success would be achieved if the failed satellites could be repaired on-orbit.

Another promising area of on-orbit operations is extension of the useful life of those satellites that are functioning successfully. These spacecraft offer two potential paths of future cost savings. First, the spacecraft whose experiment payload continues to provide useful data but whose housekeeping expendables such as fuel, cold gas, or batteries have been depleted could be refurbished on-orbit and have its mission life greatly extended. Second, those spacecraft with obsolete experiment payloads but with housekeeping subsystems that are fully operational could have both payload and expendables replaced on-orbit to provide a completely new mission. In fact, new experiments are being launched on existing or modified existing spacecraft in order to reduce the large design and development costs, thus demonstrating the compatibility of existing designs and new payloads.

While the potential of on-orbit maintenance is recognized, the use of man in an EVA mode to perform this function is limited in applications. The radiation environment which exists in some regions of space requires a substantial amount of shielding to protect man and consequently reduces his dexterity. The brevity of EVA periods reduces the amount of useful work that could be performed. In situations where the space station is a great distance from the worksite, propulsive requirements may be prohibitive and much valuable time would be spent traveling. The number of space stations to be orbited would be limited due to cost. Finally, the availability of astronauts to repair a random failure of a remote satellite is presumably low because of the tasks required of them in and around the space station. However, one thing is clear -- that man's intelligence and at least some part of his sensory and manipulatory capabilities are desired for on-orbit maintenance.

Remote manipulator systems allow man to be physically located in a safe environment, while extending his vision, feel, and motions to distant, hazardous locations. Today, manipulators have been built which possess both position correspondence as well as force reflection to provide the operator with a "feel" for his activities. In addition, a variety of terminal devices allow man to perform many tasks as well as he could manually and, in some cases, to perform tasks which he could not perform manually.

The foregoing suggests using manipulator systems in space to perform the following generic types of missions:

a. On-orbit repair.

b. On-orbit refurbishment.

c. Inspection and diagnosis of failed or degraded satellites. The purpose of this mission would be to obtain data on a failure otherwise unobtainable. These data would be of great value for redesign of follow-on spacecraft of the same family. These data could also be used for repair of the failed spacecraft.

d. Retrieval of scientific payloads or samples. Examples are retrieval of solar array sections or thermal coatings to examine radiation effects, retrieval of the detachable meteroid detection panels on Pegasus, retrieval of exposed photographic film, etc. Samples could either be deorbited or brought to a space station for analysis by astronaut scientists.

e. Other potential missions, such as erection of space structures, astronaut rescue, releasing fouled shrouds, hatches, or booms, and military missions.

These applications represent the direct extension to space of the hot lab manipulator technology already successfully applied to other areas on earth. The purpose of the study reported herein is to take a closer look at a specific remote manipulator spacecraft configuration to perform selected on-orbit repair and refurbishment missions. The remote manipulator spacecraft studied is a version configured for a single mission life. In operation it would be orbited separately to perform repair or refurbishments tasks on a selected satellite system. The study includes mission analysis and determination of system requirements. It also provides system design and system cost data, and a realistic evaluation of the system's ability to perform the missions. These data were derived in a manner which will allow both cost and technical comparisons of the scheme with alternate methods such as satellite replacement or man-attended maintenance.

SECTION 2

REMOTE MANIPULATOR SPACECRAFT SYSTEMS

A remote manipulator spacecraft system consists of a spacecraft in orbit and men in a control station located on earth or in an orbiting space station. The operator's control station is equipped with master manipulators, visual displays, and controls. The spacecraft is equipped with slave manipulators, an operator-aimed camera, and the necessary housekeeping subsystems. Control of the spacecraft is through a wideband radio link.

The NASA established ground rules restricted the investigation to a system concept of the type depicted in Figure 2-1. This is a ground controlled single mission, single vehicle system. The rationale behind this is the belief that this is the lowest cost approach. By launching a new remote manipulator spacecraft for each mission, the spacecraft are produced in larger quantities and the recurring costs are low. Furthermore, the large propulsive requirements of orbit transferring resulting from a spacecraft with a multi-mission capability are obviated. Finally, a single mission system has a short operational life which alleviates the requirements for design redundancy and long life testing and reduces the costs.

Other system concepts exist but are outside of the study scope and are not discussed.

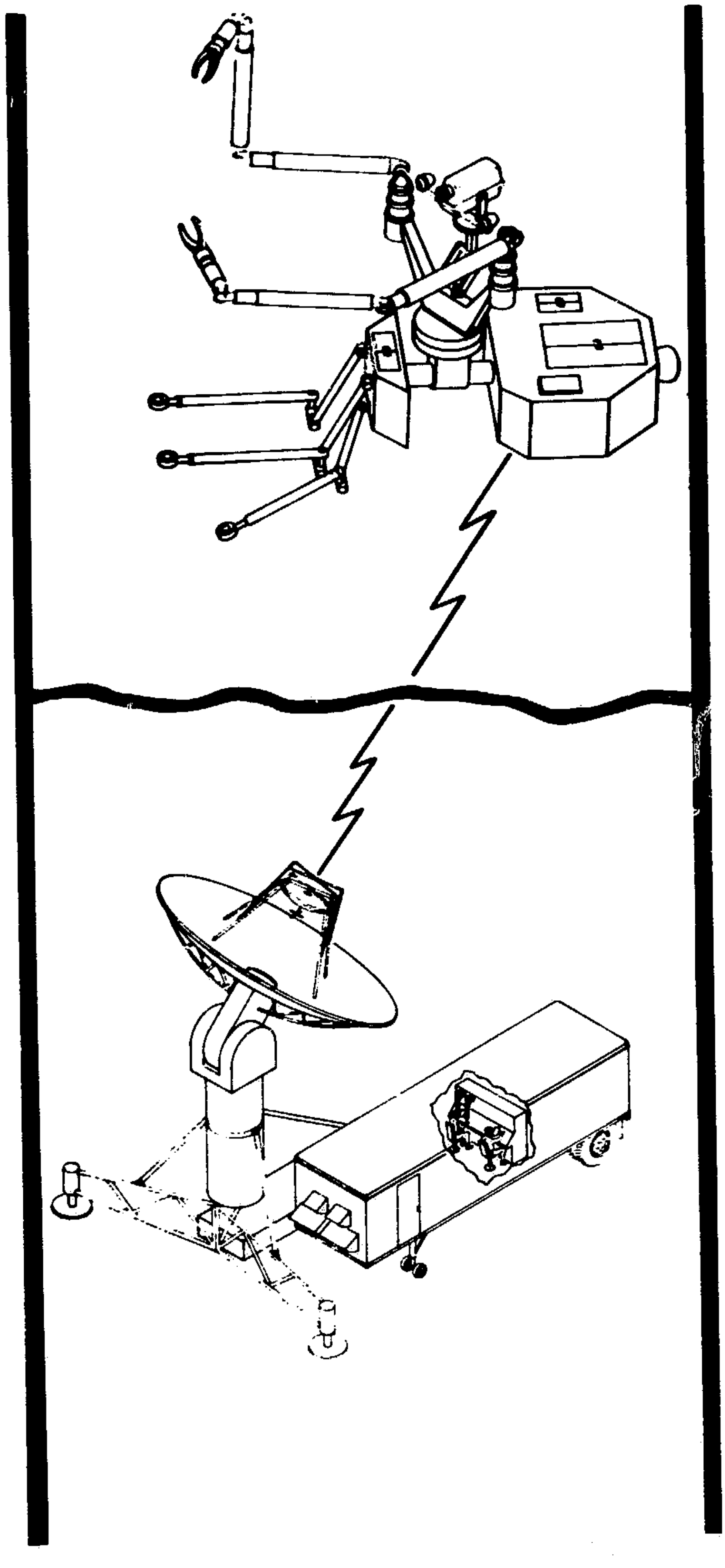


Figure 2-1. Ground Controlled Remote Manipulator Spacecraft System

SECTION 3

OBJECTIVES

This study is aimed at deriving fundamental data on the feasibility of using remote manipulator spacecraft systems to perform on-orbit satellite maintenance. The processes used to examine and establish feasibility included:

a. The selection of four satellite systems representing a broad cross section of designs and characteristics on which on-orbit repair or refurbishment missions could be performed. Analysis of the performance of these missions will yield a realistic set of requirements for which a remote manipulator spacecraft would be designed.

b. The recognition and identification of potential standard satellite design practices which could facilitate and simplify on-orbit maintenance. Although these standardized satellite design practices were selected specifically for enhancement of remote manipulator repair capability, these practices would aid an astronaut if he were called upon to perform EV maintenance.

c. The design of a remote manipulator spacecraft to meet as many of the system requirements as possible. The constraints on this spacecraft design were minimum cost, minimal complexity, ground control link only, and utilization of the spacecraft for a one-time mission.

d. A realistic reappraisal of the ability and limitations of the remote manipulator spacecraft design with regard to the total requirements of the selected four missions. Key design, technology, and operational problems were identified.

e. A cost estimate of an operational version of the selected remote manipulator spacecraft system. Costs were categorized as development, recurring, and sustaining costs.

The results of this study are intended to provide NASA with the basic information for realistically assessing the feasibility, and costs of developing and deploying a first generation remote manipulator system in space. The study furthermore identifies the areas for future analysis, design, and development required to provide a more complete understanding and more critical assessment of the missions which remote manipulators are capable of performing.

SECTION 4

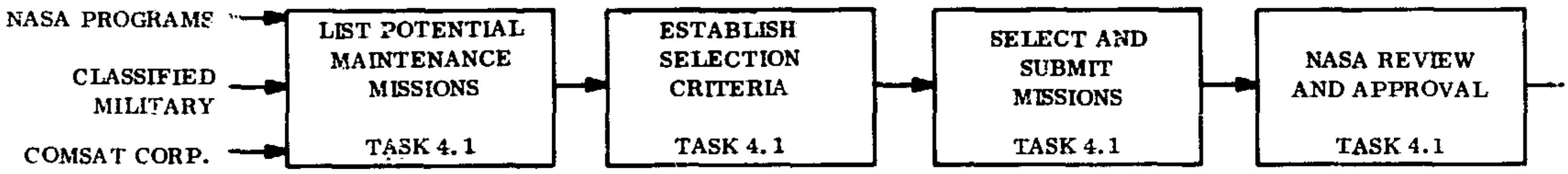
APPROACH

In order to meet the stated objectives of this study, the plan shown in Figure 4-1 was developed. The personnel participating in this study represented a mix of mission analysts, spacecraft designers, systems engineers, and manipulator design specialists from both the General Electric Company Space Systems Organization at Valley Forge, Pennsylvania and the General Electric Specialty Materials Handling Products Operation at Schenectady, New York. The laboratory facilities of the Research and Development Center were used to simulate portions of the maintenance missions. The setup included M-8 mechanical bilateral manipulators and a remote television display.

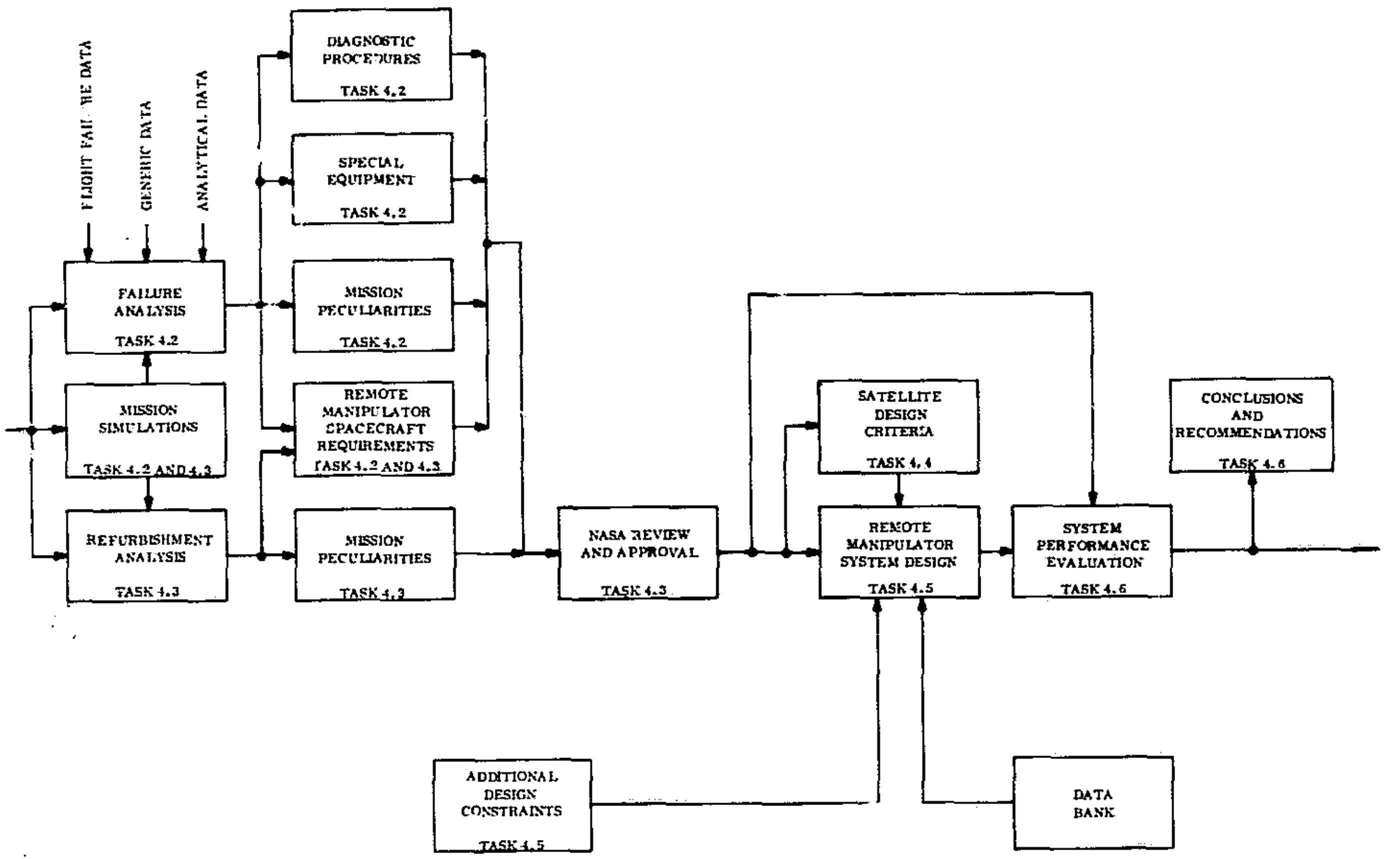
The first phase of the study dealt with the selection of two repair and two refurbishment missions from a complete listing of all NASA, unclassified military, and Comsat Corporation satellite programs. Included in the list were completed programs, programs in the hardware phase and conceptual spacecraft programs. Selections were made by assessing each satellite against a set of criteria established by the study team.

The second phase provided the design of a remote manipulator spacecraft system. The design was based on a set of requirements derived by analyzing the four selected missions. Determinations were made of characteristics such as manipulator force, torque, and reach requirements, mission duration, weight of the package containing the maintenance parts, thrusting requirements, special tool requirements, and docking equipment. Also derived from this phase were a set of satellite design practices which would facilitate future on-orbit maintenance missions by remote manipulator spacecraft.

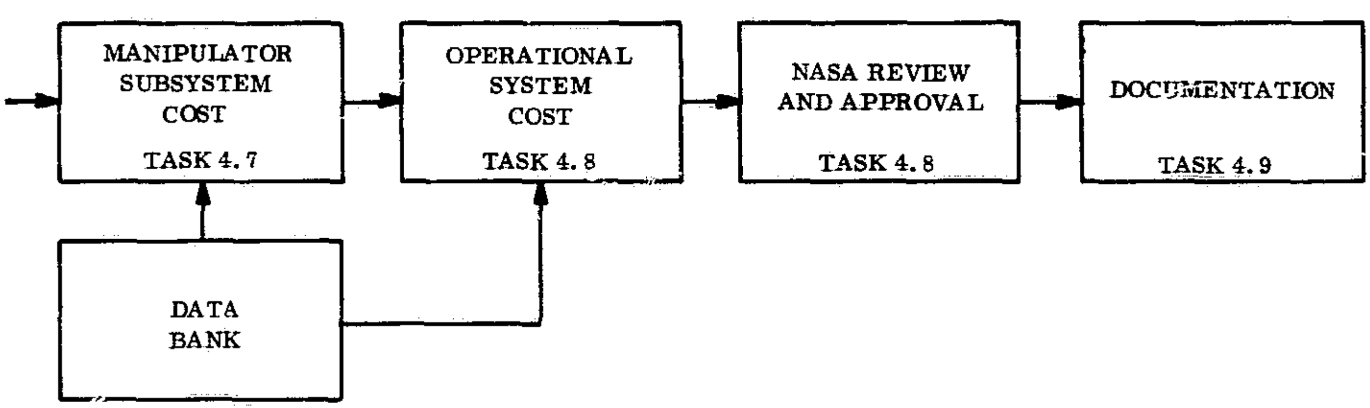
The final phase consisted of estimating the cost of an operational, remote manipulator spacecraft system. The system included spacecraft, ground station, and factory test equipment. Development, recurring, and sustaining portions of the costs were specified. Specifically singled out was the cost of a space-qualified manipulator subsystem which represented a new major technology item.



Phase I



Phase II



Phase III

Figure 4-1. Study Plan

SECTION 5

SUMMARY OF RESULTS

5.1 PHASE I - MISSION SELECTION

A complete listing of candidate satellites was compiled to ensure an unbiased field from which selection of satellites could be made that provided a broad set of requirements for the remote manipulator spacecraft system. Each satellite was assessed numerically against a set of weighted criteria and those scoring highest were selected. The satellites and missions selected appear in Table 5-1. The process and selection were reviewed and approved by the NASA Mission Analysis Division. The selections provided for low and synchronous altitude missions, stabilized, spinning, and tumbling satellites, systems that have flown, and systems that are in the conceptual stages.

5.2 PHASE II - MISSION ANALYSIS AND SYSTEM DESIGN

5.2.1 MISSION ANALYSIS

The missions selected in Phase I were analyzed to obtain system requirements. The analysis included examining hardware, photographs, drawings and documents of each satellite and consulting with personnel associated with each program. All of the steps necessary to dock, remove and replace components and refurbish expendables were defined. Manipulator force, torque, and reach were determined, and mission duration requirements were estimated. Many of the key on-orbit maintenance tasks were simulated in the laboratory using M-8 mechanical bilateral manipulators and a remote visual display. These simulations provided realistic task time data, tool requirements, and vision and illumination requirement. Figure 5-1 is a photograph of the laboratory setup. Actual full scale engineering models of the OAO and Nimbus satellites were examined to derive reach, docking, and access requirements. The key results of the mission analyses are listed in Table 5-2.

The problem of docking with each of the four satellites was analyzed and the results are summarized in Table 5-3. Docking with spin-stabilized satellites is a simpler problem than docking with an uncooperative tumbling satellite because the satellite spin axis and

Table 5-1. Satellite and Mission Selection

Satellite	Mission	Altitude (nm)	Dynamic State
FOR REPAIR			
Orbiting Astronomical Observatory (OAO)	Repair the flight failure that occurred on OAO-I	500	Tumbling at 0.5 RPM Tumbling at 34.0 RPM
Orbiting Solar Observatory (OSO)	Using generic failure rate data, apply a component failure and perform the repair	350	Spin stabilized at 26 RPM
FOR REFURBISHMENT			
Direct Broadcast Satellite (DBS) - Voice Broadcast Mission - UHF	Replace the DBS transponder with a transponder more suitable for the new mission	19,323	Actively stabilized
Nimbus	Replace the meteorological sensors with improved sensors for a new mission. Replenish the expendables.	500	Actively stabilized

Table 5-2. Mission Analysis Summary

Mission	Duration (Minutes)	Maintenance Package Weight (Pounds)	Maximum Manipulation			Laboratory Task Simulations
			Reach (Inches)	Force (Pounds)	Torque (Inch-Lbs)	
OAO-A1 Repair	986	405	40	20	40	Yes
OSO-D Repair	265	31	40	15	40	Yes
DBS-VBM/UHF Refurbishment	494	110	40	15	40	Yes
Nimbus A-C Refurbishment	754	166	40	15	40	Yes
Nimbus D-E Refurbishment	287	1090	40	15	40	Yes

Table 5-3. Results of Docking Analysis

Satellite	Results	Docking Procedure Comments
OAO	1. Docking would not be attempted at tumbling rates higher than 1.5 rpm.	1. Limited by operator control authority 2. Limited by potential danger due to motion of satellite spin vector in space
	2. Use of manipulator-held fluid jets to impinge and reduce satellite energy was found feasible.	1. Required large quantity of cold gas. Hot gas more attractive but may be contaminatory in some cases.
OSO	De-spinning would be accomplished with special manipulator-held and operated de-spinning devices	Figure 5-2 illustrates one of three such devices configured.
DBS	The satellite is actively stabilized and cooperative. Docking is straightforward.	
Nimbus	The satellite is actively stabilized and cooperative. Docking is straightforward.	

rate are known prior to the launch of the remote manipulator spacecraft. Therefore, special de-spinning devices could be built prior to the missions and sent along with the remote manipulator spacecraft.

The manipulator requirements for all missions are very similar, suggesting the suitability of a single design for orbital maintenance operations. These requirements are very close to man's capabilities and, hence, make the manipulator man-equivalent and interchangeable with an astronaut. Special tools are required to provide high force or torque levels. This need, however, occurred infrequently in the missions studied and for short periods.

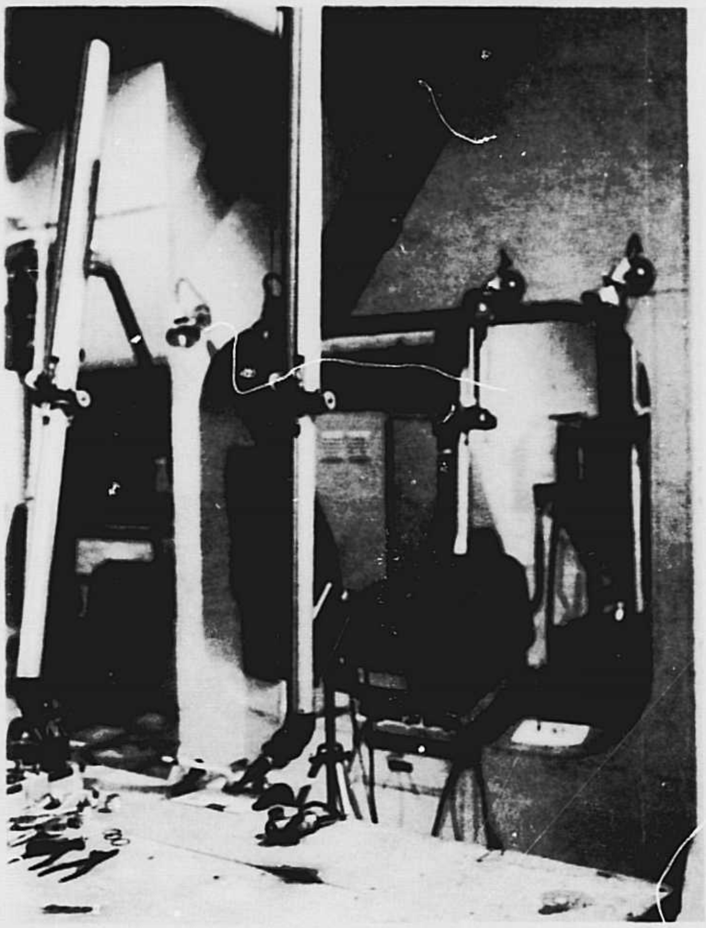


Figure 5-1. Laboratory Setup

Another important result of the mission analysis was the identification of satellite design practices which would ease on-orbit maintenance operations by either a remote manipulator spacecraft or an EV astronaut. These practices were established during the step-by-step analysis of each mission. Some typical recommendations are listed by mission phase in Table 5-4.

A remote manipulator spacecraft system was configured, based on the requirements resulting from the mission analyses. The system consists of a remote manipulator spacecraft, a ground control station, and ground support equipment at the manufacturer's facility and at the launch pad. The major design requirements for the system are listed in Table 5-5. Figure 5-3 is a system functional flow block diagram showing the interfaces between the subsystems in the ground control station and the spacecraft and the interfaces between these two system elements.

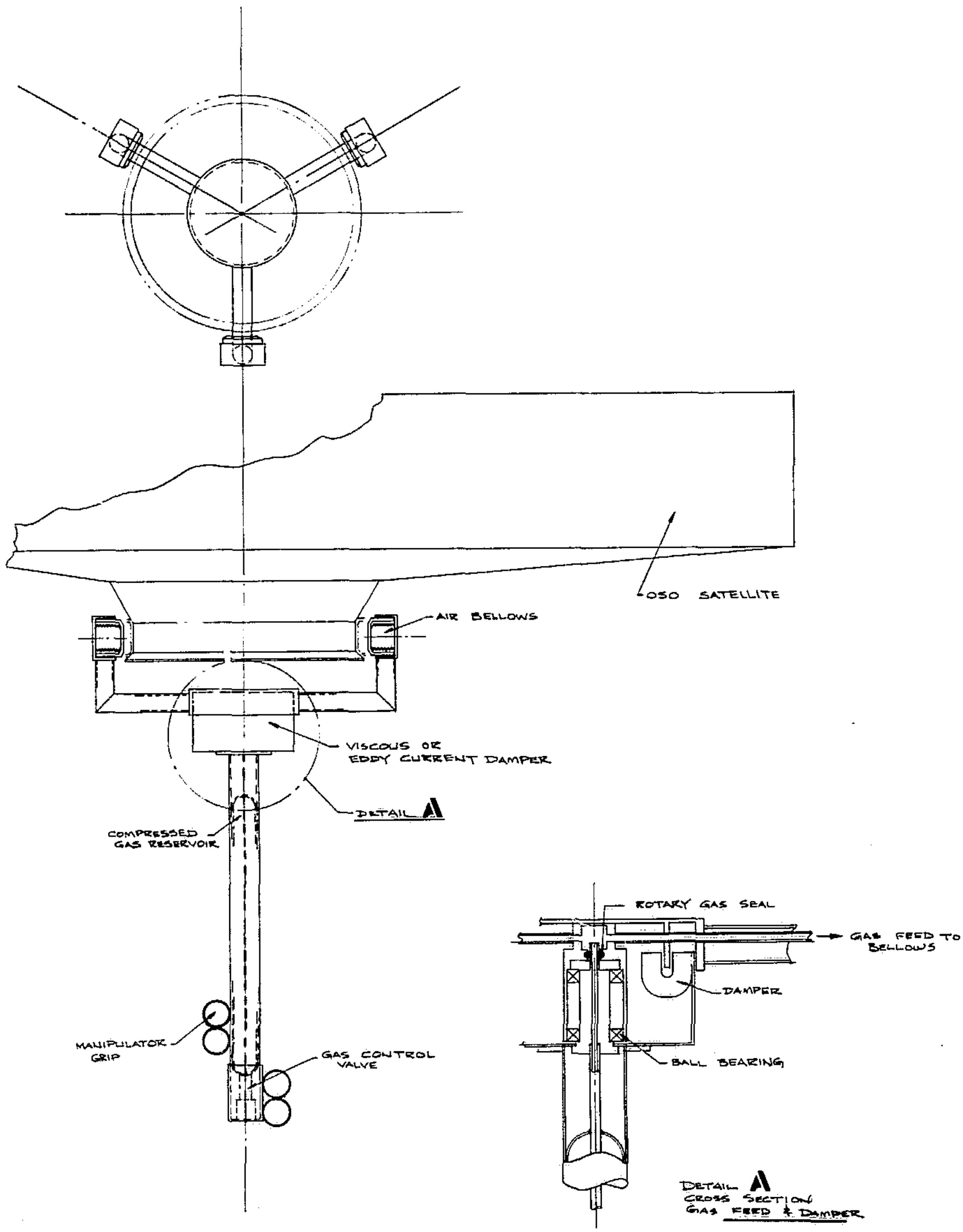


Figure 5-2. OSO-D Despin Fixture

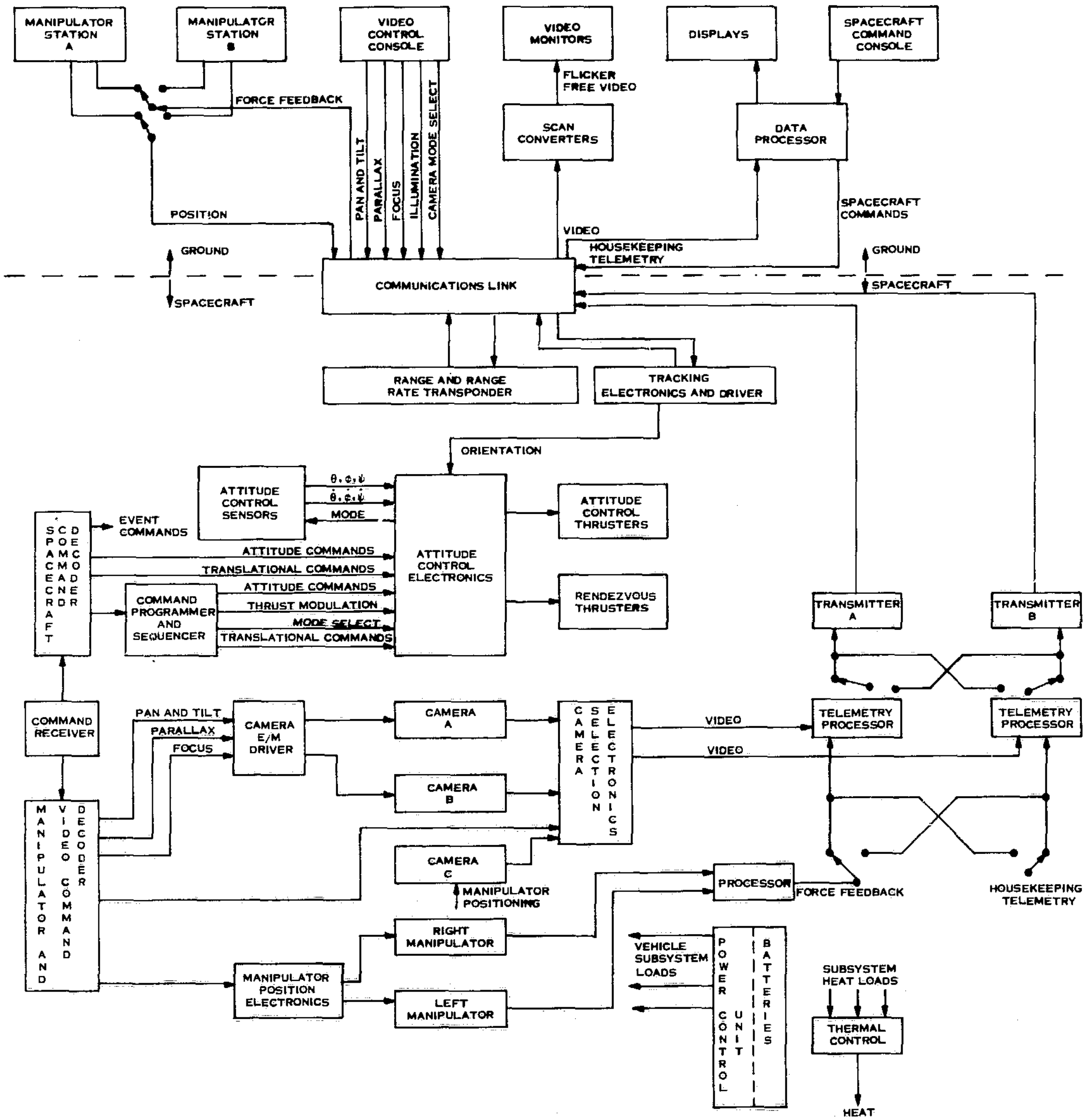


Figure 5-3. System Functional Flow Block Diagram

Table 5-4. Examples of Satellite Design Practices for Ease of On-Orbit Maintenance

Pre-docking	1. Jettisoning of satellite masses such as propellant, hazardous equipment, booms, antennas, etc. in preparation for docking 2. Emergency command systems (self-powered) to activate, control or deactivate the parts or the entirety of the satellite system. Backup manual switches and disconnects on the satellite itself also are recommended.
Docking	1. Development of docking hardware such as gripholds, grapple lattices, docking cones, guide rails, etc. 2. Onboard, extendable tethers or rods, booms, etc., that could reel in a remote manipulator spacecraft
Repair/Refurbishment	1. Multiple work platforms and docking hardware wuch as grip holds and grip rails. 2. Single motion, quick-disconnect, highly accessible service connections. 3. Adequate clearances for tools, connectors, modules, fixtures, subassemblies, and tether grips. 4. Minimum sequential assemblies and logical assembly procedures. 5. Provision of alignment surfaces, pins, or indices. 6. Identification of satellite axes 7. Modularized subsystems or assemblies
Diagnosis	1. Leak detection aids such as dyes, depositions, fluorescences, odor, and radiation. 2. Easily identified and probed test points.

5.2.2 SPACECRAFT DESIGN

The repair and refurbishment payloads for each of the missions were packaged in the remote manipulator spacecraft. Figures 5-4 and 5-5 show the launch configurations for two of the missions. Figure 5-6 shows the remote manipulator spacecraft deployed to its orbital configuration and Figure 5-7 is a three-view drawing of the spacecraft. The spacecraft subsystem weight and power summary is given in Table 5-6.

5.2.2.1 Manipulators and Docking Tethers

The manipulator characteristics are described in Table 5-7. Each manipulator has three transport and three rotational degrees of freedom with an indexing joint at the shoulder A drawing of the slave unit is shown in Figure 5-8. The servo package is mounted at each joint obviating the use of cable or tape drives. This reduces weight and complexity, provides a stiffer system which helps stability, and enables the arms themselves to serve as heat sinks. The joints are offset to allow compact folding during launch. Each of the

Table 5-5. Major System Design Requirements

1. The remote manipulator spacecraft shall have a minimum design life of 10 days in orbit.

2. The spacecraft shall be capable of being launched on the DSV-2L, two-stage Delta booster with the standard shroud. (Selection of a launch vehicle was not required by NASA. The General Electric Company selected a launch vehicle in order to establish a launch configuration design constraint by way of the booster shroud. The DSV-2L was selected because it was the least costly booster available which met the required payload capability.)

3. The basic spacecraft shall be identical for all missions. Differences shall exist only in spare parts, tools, test equipment, and quantity of expendables peculiar to each mission.

4. The spacecraft shall be capable of performing a rendezvous maneuver to bring it from the booster separation point to the target satellite. The rendezvous actions will be by ground command and will be based on ephemeris data provided by the assigned tracking facility.

5. Communications between the ground control station and a remote manipulator spacecraft at low or medium altitudes shall be via an assumed operational date relay satellite system.

6. Communications between the ground control station and a remote manipulator spacecraft at synchronous altitude may be direct or via an assumed operational data relay satellite.

7. Full-time communications between the ground control station and the spacecraft shall be maintained.

8. The ground control station and ground support equipment shall be capable of repeated operations with minimum maintenance.

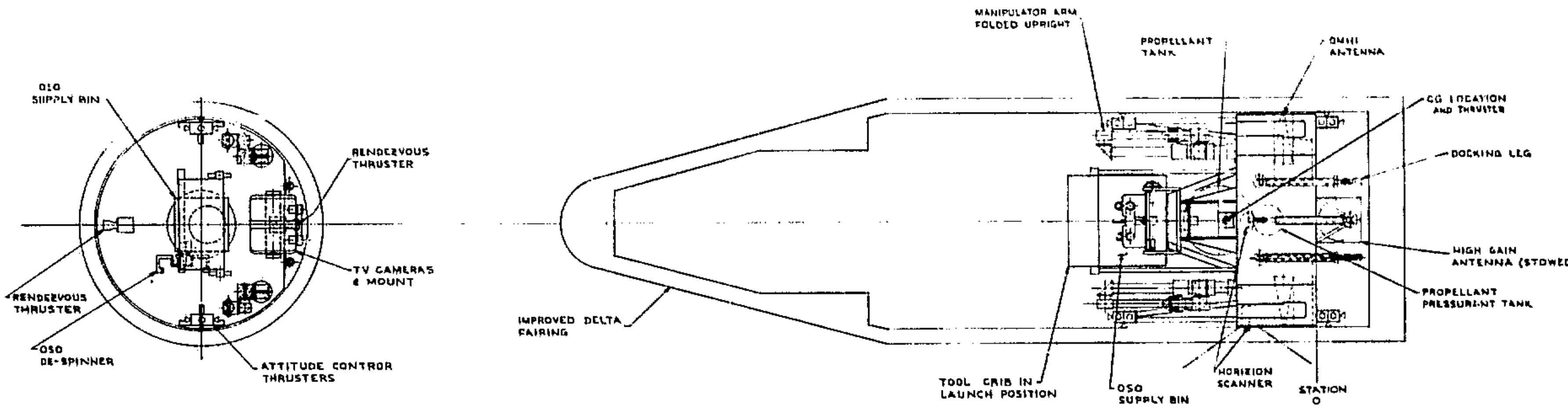


Figure 5-4. Launch Configuration OSO Mission

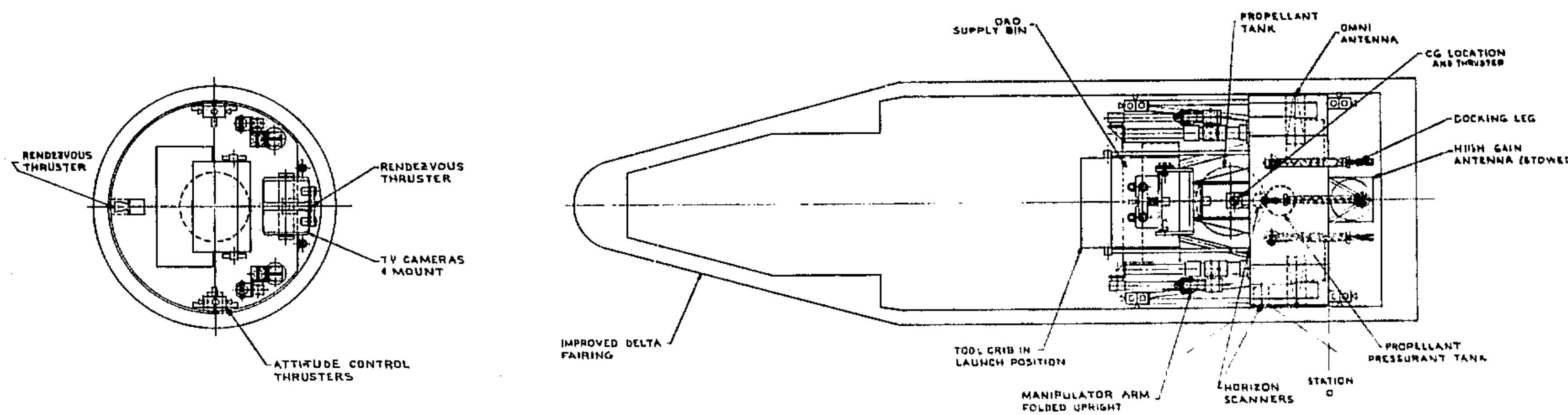


Figure 5-5. Launch Configuration OAO Mission

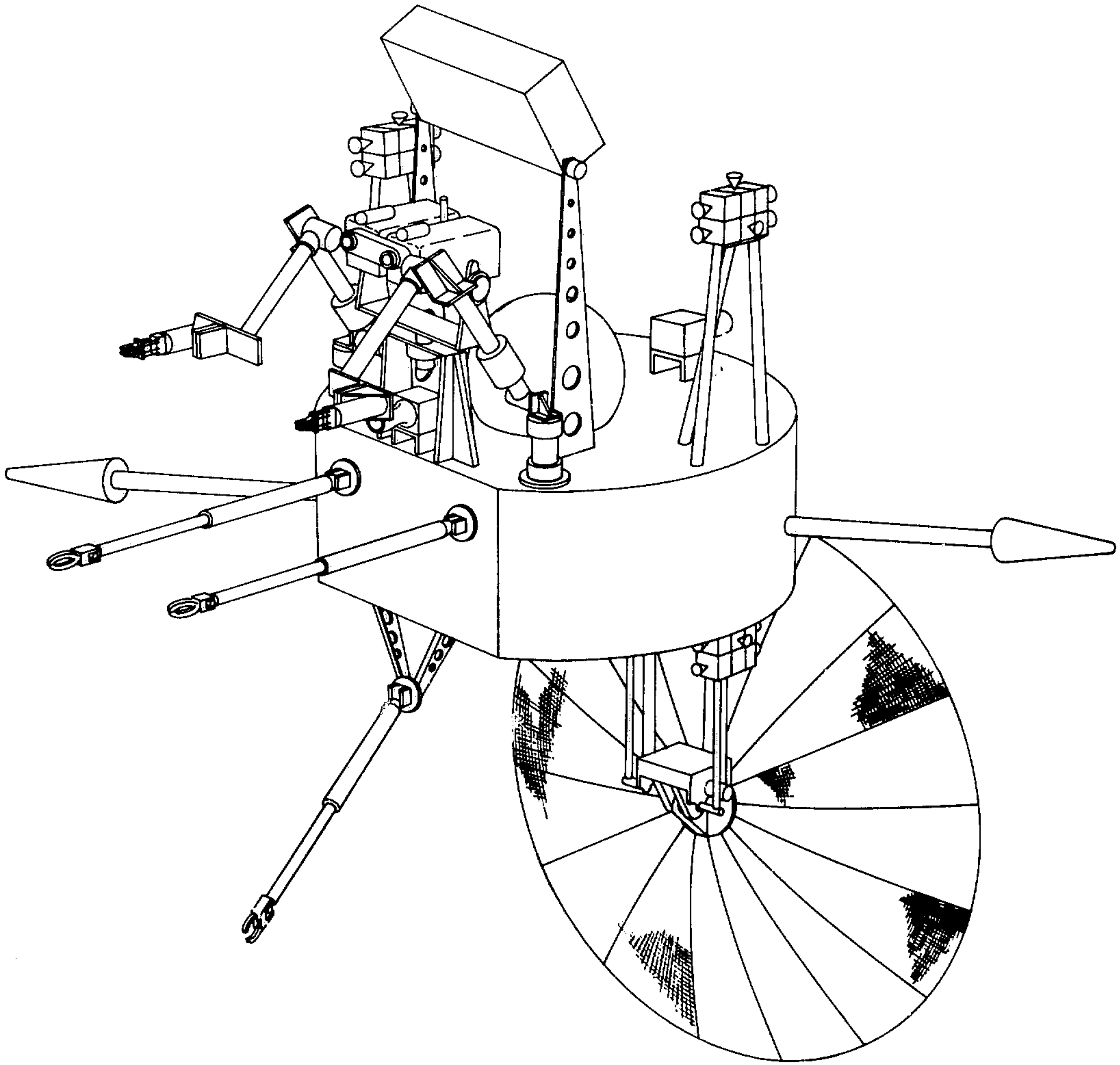


Figure 5-6. Orbital Configuration of Remote Manipulator Spacecraft

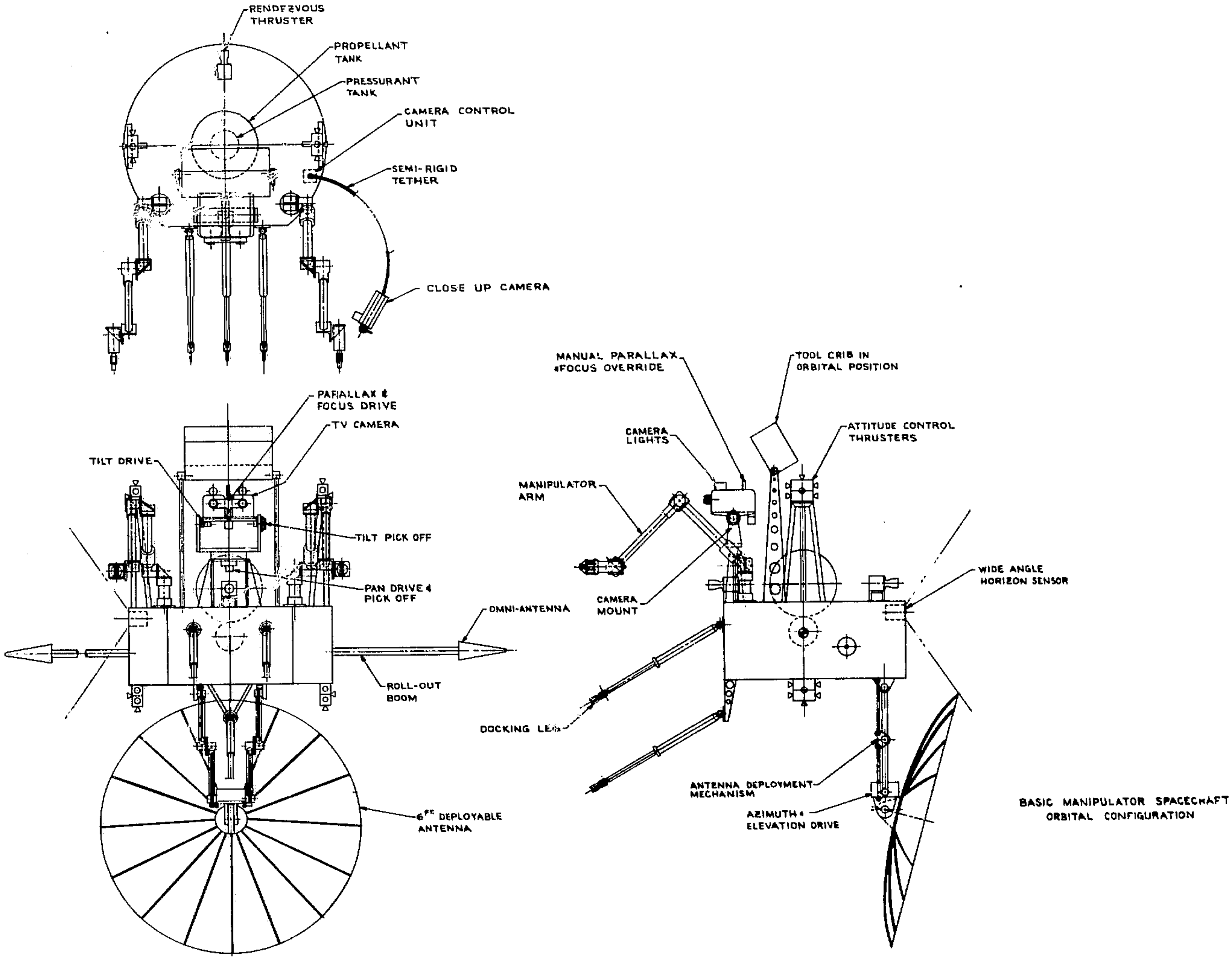


Figure 5-7. Three View Drawing of Remote Manipulator Spacecraft

Table 5-6. Basic Spacecraft Weight and Power Summary

Subsystem	Weight	Power (Watts)	
		Maintenance Phase	Peak
Propulsion (with Fuel)	123.3	--	150
Attitude Control Reference	40.4	40	86
Power Supply	408.0	--	--
Communications	124.3	76.5	166.5
Manipulators and Docking Tethers	104.0	43 (Both Manipulators)	600
Vision and Lighting	44.1	44	75
Structure and Thermal Control	124.0	--	--
Total	968.1	203.5	1077.5

Notes: Total electrical energy requirement for a 10-day mission is 25,000 watt-hours
Total electrical power subsystem capability is 37,500 watt-hours.

Table 5-7. Manipulator Characteristics

Parameter	Description
Configuration	Two six-degree-of-freedom arms
Type	Electrical bilateral, i.e., closed loop position control with force feedback
Reach	40 inches, spherical envelope
Resolution	0.04 inch
Force	15 lb per arm at maximum reach
End Effector	Parallel jaw tongs
Indexing	Two shoulder joints
Life	Approximately 10 days in orbit
Velocity	30 inches per second maximum
Weight (each including amplifiers)	43 pounds
Power (each)	
Peak	300 watts
Average	21.5 watts

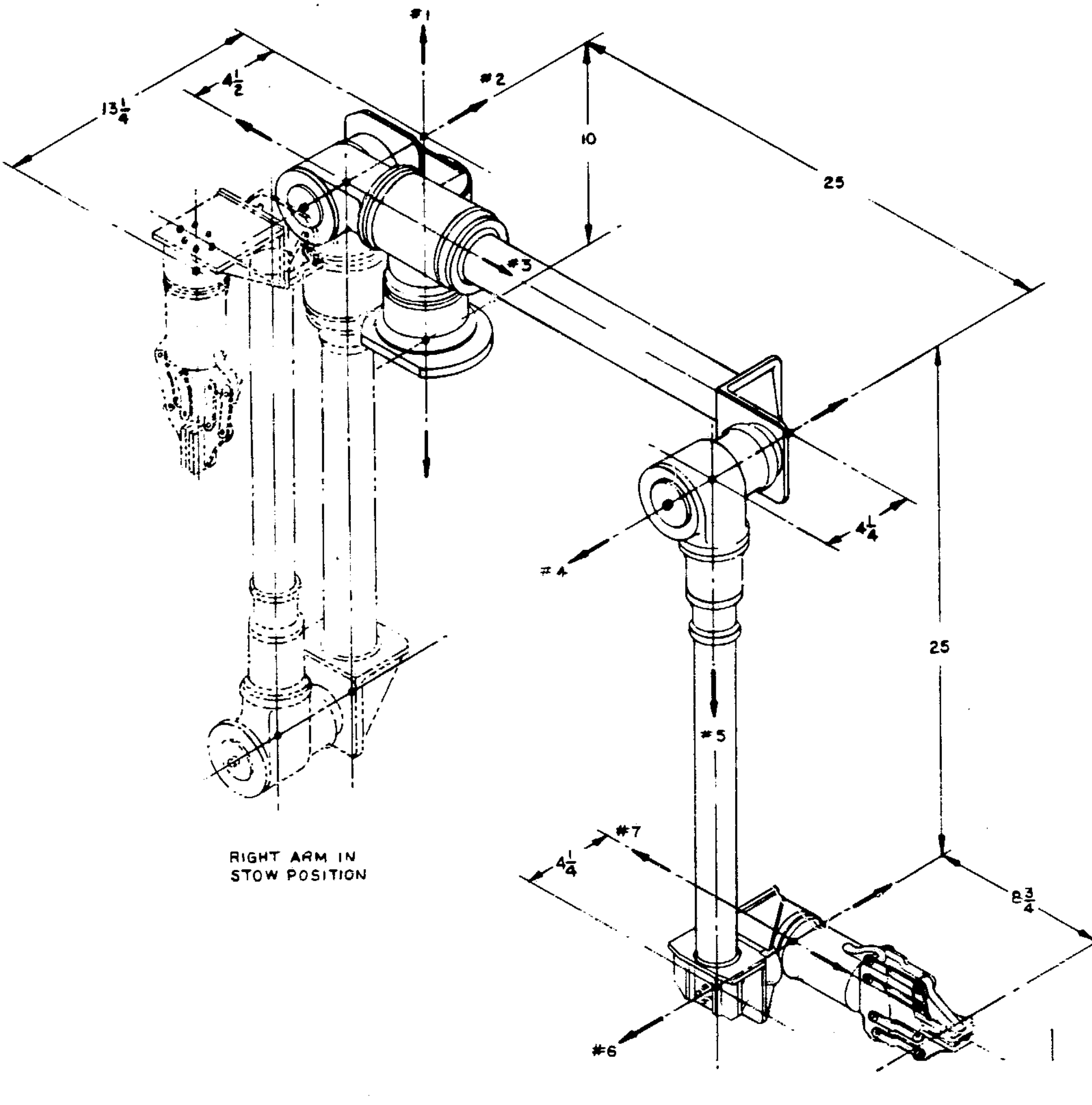


Figure 5-8. Isometric of Slave Manipulator

joints are identical in design. A standard unsealed harmonic drive is proposed in place of a conventional gear train, resulting in a large weight saving. A silicone grease would provide adequate lubrication for the ten day life. Standard torque motors and film-type potentiometers provide the torque and pick-off signal at the joint. The docking tethers are passive and are attached by the manipulator.

5.2.2.2 Communication Subsystem

Figure 5-9 is a block diagram of the Communications Subsystem. The Radio Subsystem receives RF signals on two frequency channels and transmits RF signals on three frequency channels via two omnidirectional antennas and one high-gain tracking antenna. The frequency assignment is:

Uplink

Frequency	Designation	Use
2253 MHz	D1	Range and Range Rate
1831..8 MHz	U2	Manipulator Control, TV Camera Control, Satellite Commands

Downlink

Frequency	Designation	Use
1700	D1	Range and Range Rate
2272.5 MHz	D2	TV Signal, Force Feedback
2285.5 MHz	D3	TV Signal, Engineering Telemetry

The Command Subsystem processes the received signal from the Radio Subsystem to recover and distribute the manipulator control, TV camera control, and satellite command data. The Data Handling Subsystem processes the two TV signals, 14 force feedback PCM signals, and the engineering telemetry to provide two composite baseband signals to the Radio Subsystem for transmission to the ground station. The range and range-rate transponder receives up to three STADAN ranging signals in the same frequency channel from

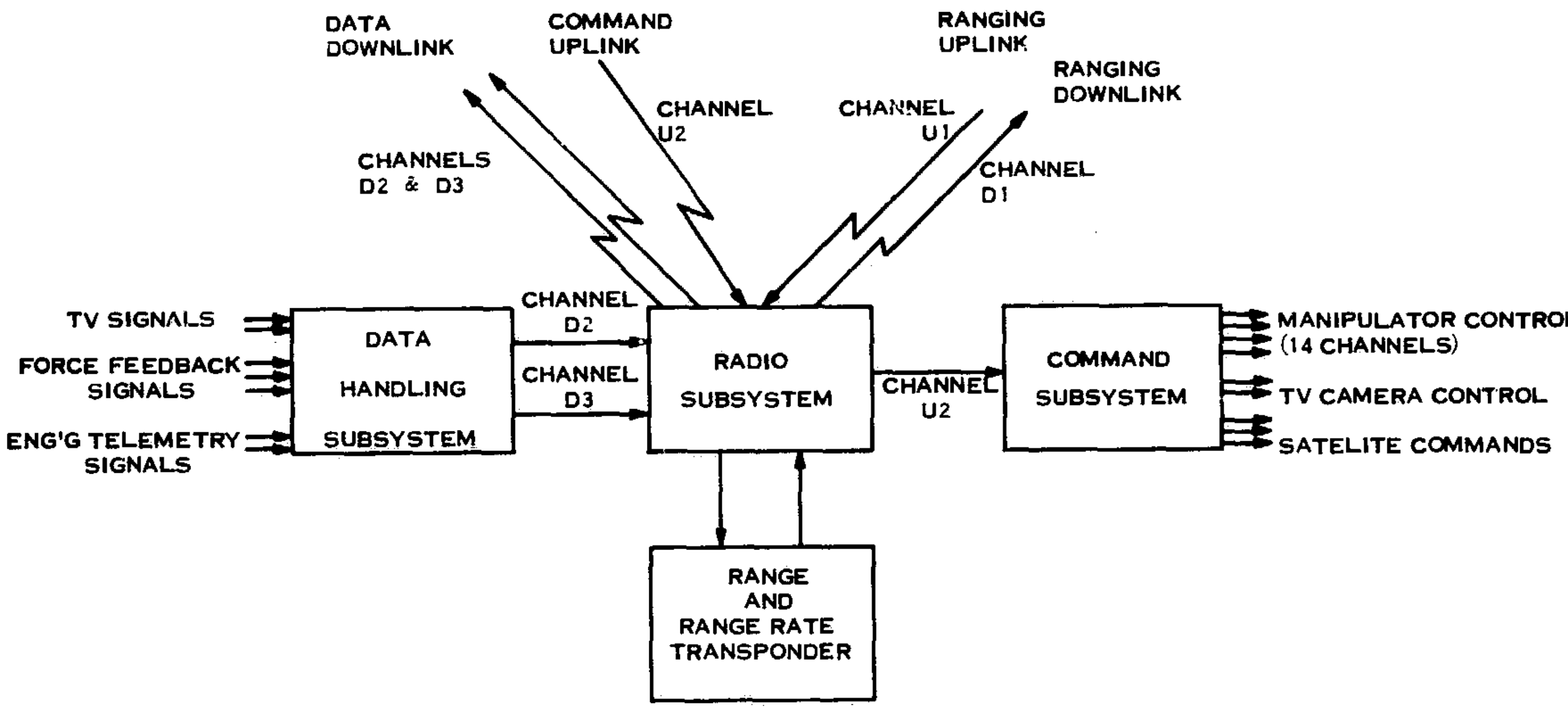


Figure 5-9. Communications Subsystem Block Diagram

the Radio Subsystem, coherently translates the frequency of each to the proper downlink frequency and sends the composite ranging signal to the Radio Subsystem for transmission to the tracking facilities.

5.2.2.3 Propulsion Subsystem

A common blowdown monopropellant hydrazine subsystem is used for randezvous, maneuvering, docking, and stabilization. A schematic diagram of the subsystem is shown in Figure 5-10. The subsystem contains two tanks (for the pressurant and propellant), and explosive-actuated isolation valve (pyro valve),filter, two 26-pound thrust rendezvous engines, eight 2-pound thrust and sixteen 0.5-pound thrust maneuvering and attitude control engines. The tanks and engines are all space-qualified. The location of the rendezvous engines can be varied from mission to mission so that their thrust is through the c.g. The smaller thrusters used for attitude control and maneuvering have fixed locations which were chosen to minimize the plume impingement on the target vehicle.

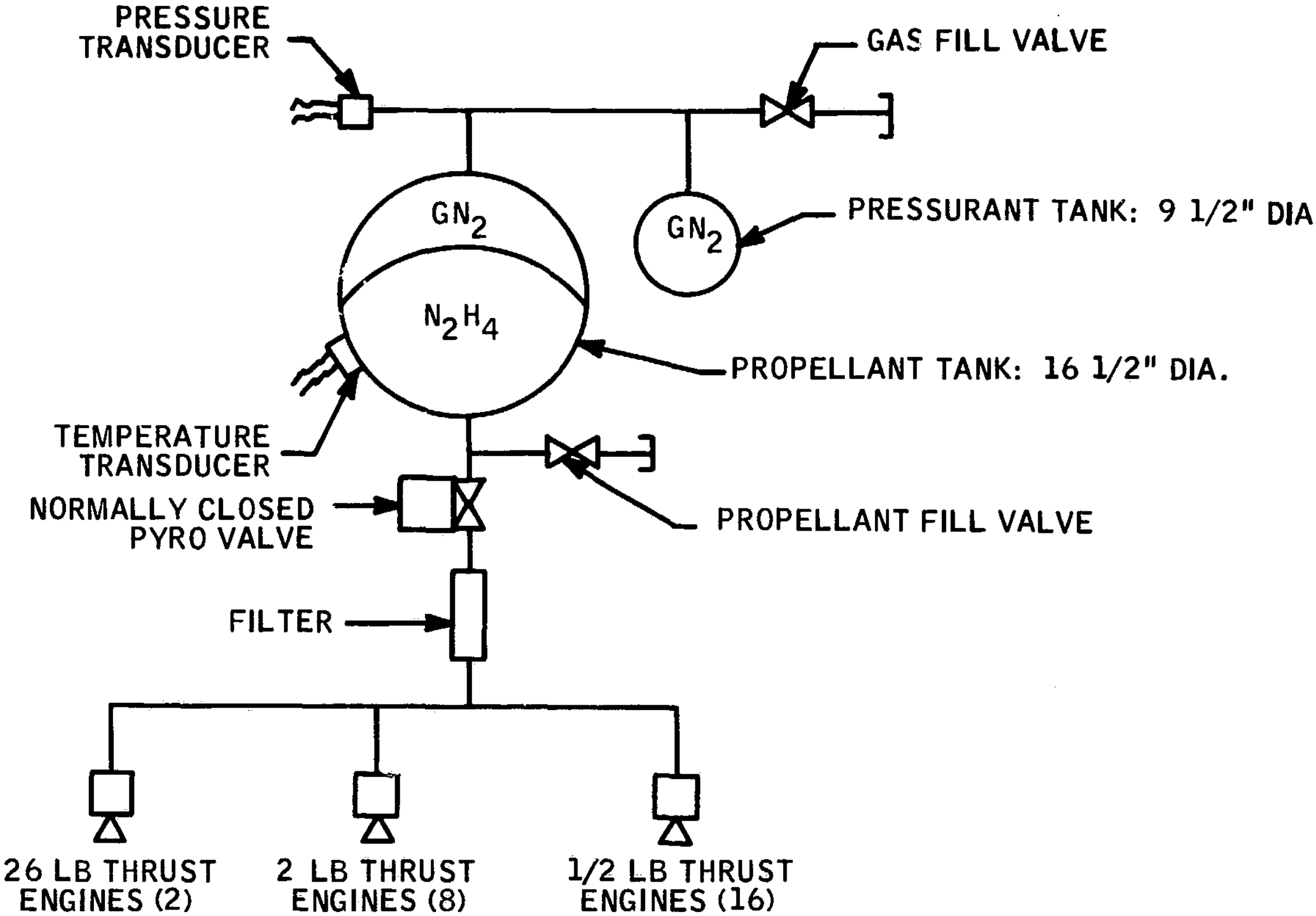


Figure 5-10. Propulsion Subsystem Schematic

5.2.2.4 Vision and Lighting Subsystem

This subsystem consists of a high-resolution stereo TV section that mounts two camera assemblies on a moveable platform to provide pan, tilt, parallax control, and focusing capability that is controlled by the manipulator operator on earth. A mechanical backup is achieved by allowing the manipulators to physically position the pan-tilt assembly and adjust the focus and parallax control in case any drive unit fails. A third camera head assembly, located within reach of the manipulator, is attached to a semi-rigid tether, so that it may be placed in any position for close viewing of the work area. Figure 5-11 shows the video and illumination subsystem schematic.

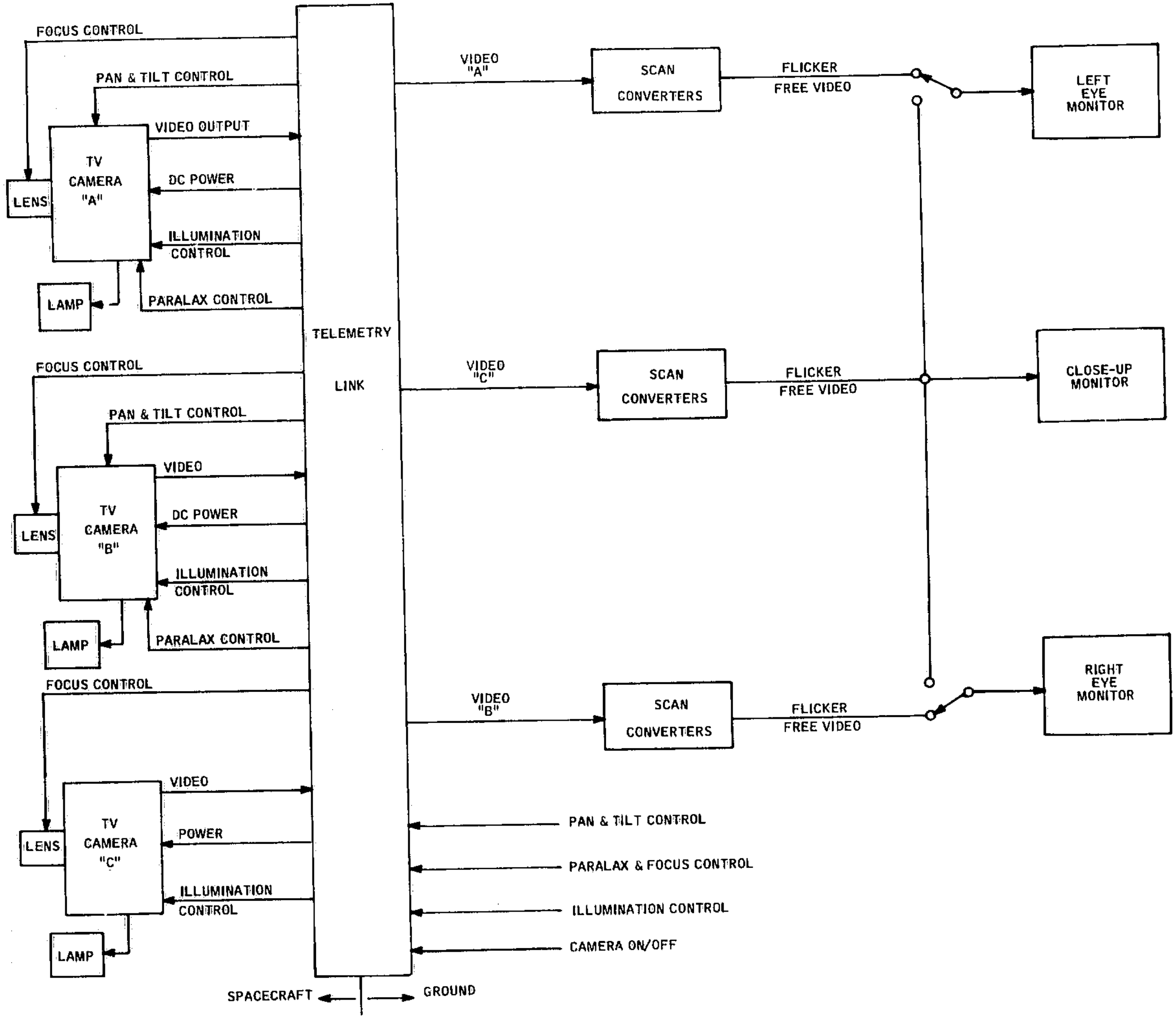


Figure 5-11. Video and Illumination Subsystem Schematic

Table 5-8 describes the characteristics of the cameras.

Table 5-8. Camera Characteristics

Characteristic	Value
Aspect Ratio	4 by 3
Frame Rate	10 frames per second
Line Rate	525 TV lines per frame
Bandwidth	1.4 MHz
Spectral Response	S-18
Illumination Requirements	High light level - 155 foot candles per square foot

The camera lens was not chosen but some of its parameters are known. The paired cameras should be able to focus from 10 inches to infinity and have and adjustable focal length to allow the field of view to vary from the narrow angle required for rendezvous to the wide angle required for inspection. Field of view variation from 10 to 60 degrees is desirable. This would have to be based upon the availability of variable focal length lenses since a turret to change lenses does not appear desirable with the present focusing method. The close up camera would use a fixed focal length lens providing a 25 to 30 degree field of view and be able to focus from 3 inches to 6 feet.

The illumination portion consists of three 5-watt incandescent lamps with reflectors, three Automatic Light Control (ALC) mechanisms, and two reflector/diffusers. One lamp and one ALC is mounted to each of the three cameras (Figure 5-8). Reflectors/diffusers will be stored within reach of the manipulators for use when required. Although there does not appear to be a space qualified camera available with the necessary characteristics at this time, cameras are available that are qualified for military aviation and a minimum amount of modification is necessary to make them useable in space.

5.2.2.5 Attitude Control Reference Subsystem

This subsystem consists primarily of three strapped-down rate integrating gyros, two IR horizon scanners, an electronics package designed to provide all necessary computation, amplification, integration, addition, logic, and switching functions, and twenty-six solenoid drivers. The subsystem is capable of functioning in three modes: an inertial reference mode which is used during initial stabilization, rendezvous, thrusting, docking, and tracking antenna transfer; a fine sensing mode which updates the gyros using the IR horizon scanners and a ground commanded yaw signal (used during initial acquisition and if antenna track is lost); and a coarse attitude control mode which is used during the rendezvous phase and after docking, but not while transferring between relay satellites. This mode reduces propellant consumption and thus reduces the contamination potential. The subsystem has a 3 σ pointing accuracy of 1.5 degrees about all three axes. Attitude control after docking is achieved by using the video subsystem output showing the docking point and ground computing the new center of mass and principal moments of inertia. A new thruster firing sequence and duration is ground computed and inserted into subsystem memory units which then apply the correct torques for error signals from each of the three attitude sensors.

5.2.2.6 Electrical Power Subsystem

The Electrical Power Subsystem (EPS) provides and distributes electrical power to the spacecraft. Figure 5-12 is functional block diagram of the EPS. The electrical energy source is a set of three silver oxide-zinc batteries, providing approximately 445 ampere-hours of energy per battery. The interface between ground power and internal power is provided by the Power Control Unit (PCU). This unit provides battery isolation for failure protection and also provides telemetry for energy management and monitoring of critical subsystems.

Figure 5-13 shows the manipulator spacecraft prime power profile for a 24-hour period. This power requirement is assumed to repeat each day for the 10 days of the orbital mission. Actually, the total power requirements of the first and last days may be somewhat less because manipulator activity on these days will be minimal. The first day will be devoted

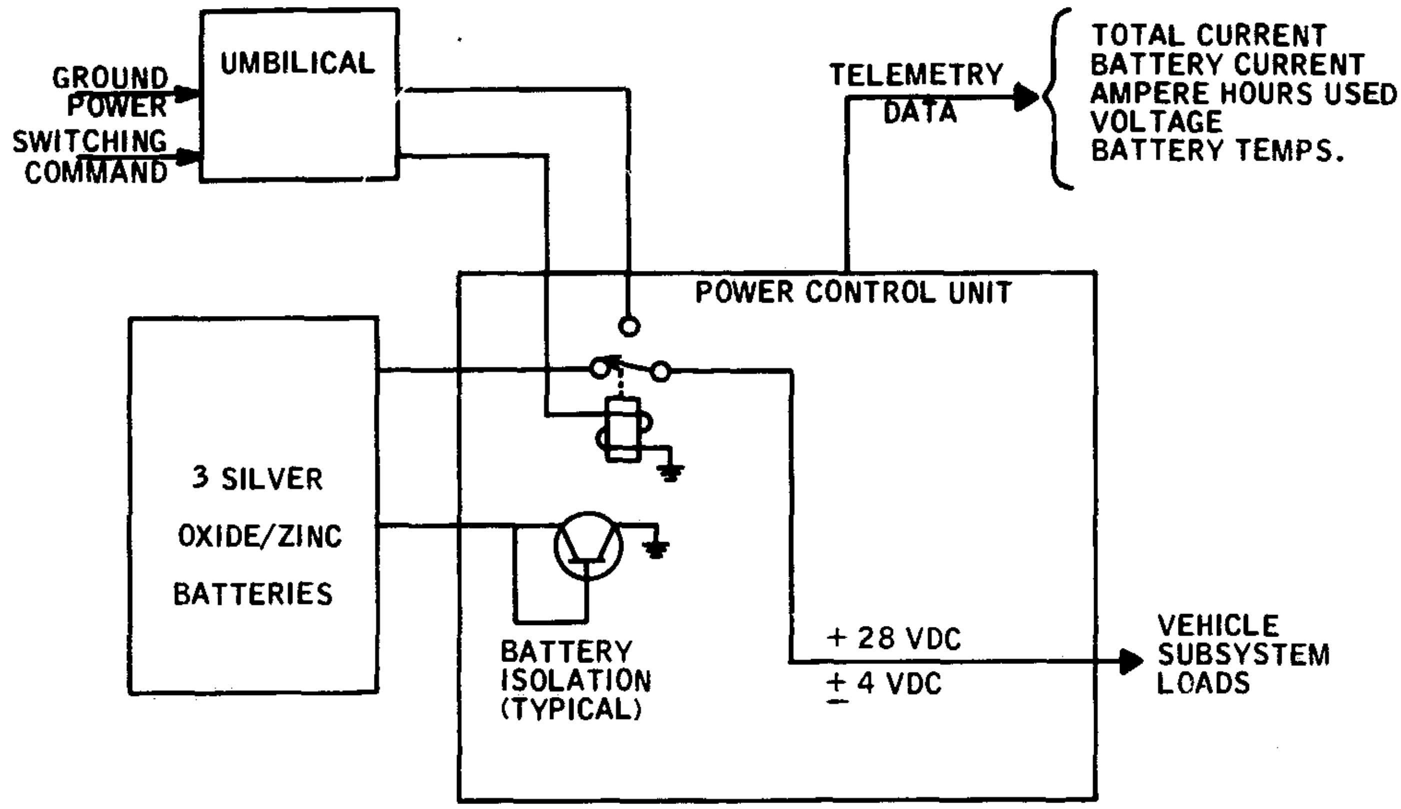


Figure 5-12. Electrical Power Subsystem Block Diagram

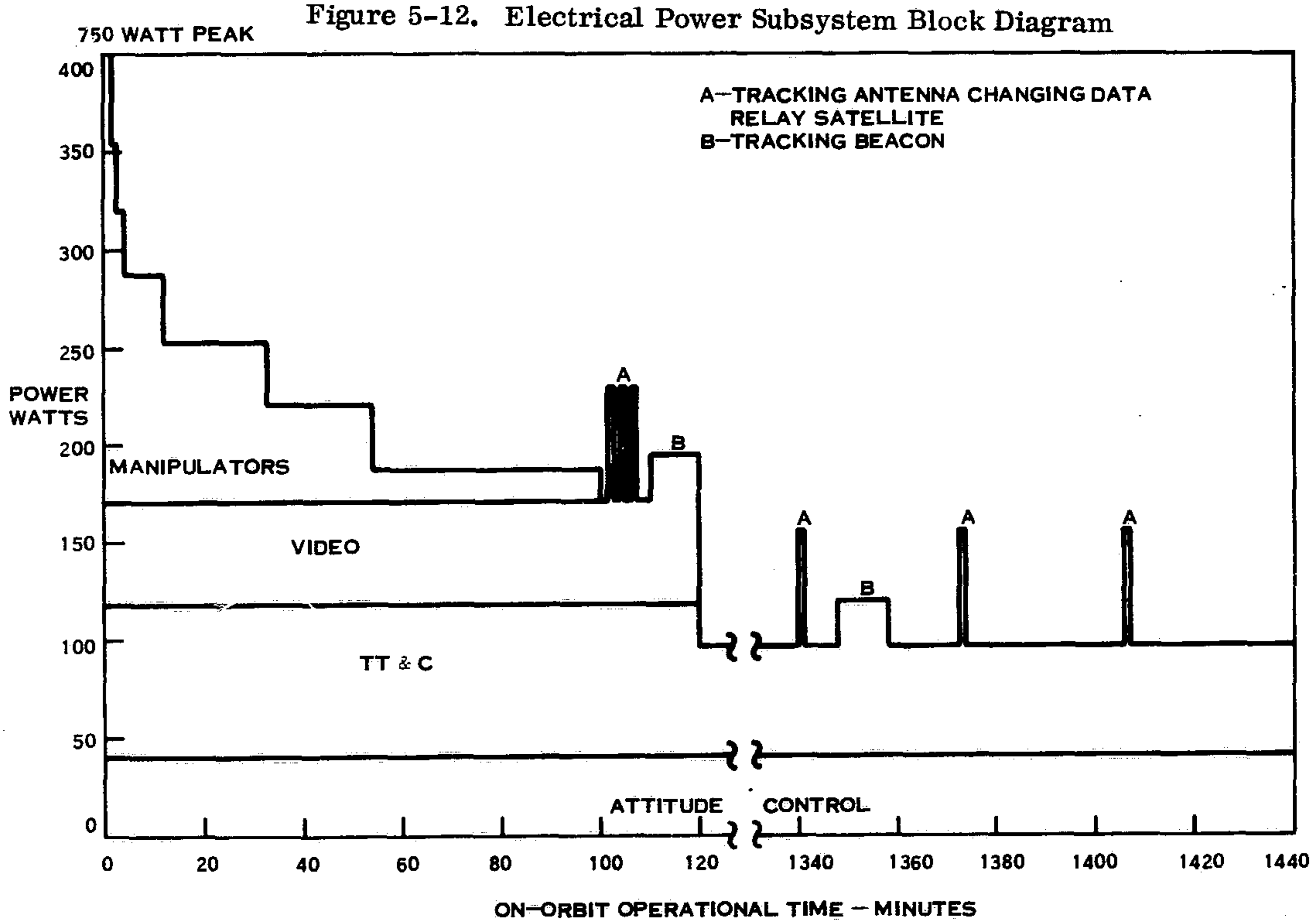


Figure 5-13. Manipulator Spacecraft Prime Power Profile

to rendezvous and docking and the last day would see the manipulator leaving the target vehicle, observing the orbital operation of the target satellite, and then retro-thrusting out of orbit. Each period is arbitrarily started with the manipulator activity which continues for two hours.

The total electrical energy required for the 10 day mission is calculated to be less than 26, 000 watt-hours and peak power requirements occurring during manipulator operation may be as high as 750 watts. The three silver oxide-zinc batteries provide 37, 500 watt-hours.

5.2.2.7 Structure Subsystem

The remote manipulator spacecraft structure is cylindrical, comprised largely of ribs emanating from an internal, central cylinder and attached to an external cylinder. The external cylinder, along with the top and bottom skins, thermally and mechanically protects the internal housekeeping equipment. This non-monocoque structure construction, which is typical of satellite construction, has been selected for several reasons:

- Almost all of the loads imposed by the spacecraft subsystems on the structure are concentrated loads rather than uniformly distribute loads.
- The ribs provide many versatile mounting surfaces to control the spacecraft c.g. and provide for spacecraft development and growth.
- The ribs also function as heat sinks and heat distribution aids.
- The ribbed construction allows the outer surface of the cylindrical base to be (1) scalloped for storage of the manipulators, and (2) designed for thermal shutters and access doors to the housekeeping subsystem.
- The ribs form compartments that isolate the various housekeeping subsystems against environmental or emergency problems.
- The ribbed construction transfers the launch loads between the booster adapter and all of the spacecraft subsystems.
- The ribbed construction stiffens the spacecraft both flexurally and torsionally without requiring structural doors or thick skins on the upper and lower surfaces of the cylindrical base.

5.2.2.8 Thermal Control Subsystem

The spacecraft thermal control subsystem is largely passive for the following reasons:

1. The short, 10-day mission-life requirement allows high equipment operating temperatures.
2. In case of unexpected thermal control problems, the spacecraft and the attached satellite can be oriented by the ground operator because of the versatile view angles of the IR earth sensors and high-gain antenna. Furthermore, the spacecraft can erect and position thermal and light shades, diffusers, and reflectors to thermally control the manipulator and target spacecraft.
3. Almost all of the replacement equipment is thermally protected because it is inside the supply bin. The exposed replacement equipment can withstand the thermal environment as well as it does during the regular missions of the satellites.

The subsystem consists primarily of coatings of appropriate absorptivity/emissivity coefficients.

5.2.3 GROUND STATION DESIGN

The ground station is the nerve center of the system. All actions and decisions are made there. The ground station design must not only provide accessibility to data banks, high speed computational capabilities, adequate displays and controls, but must also have the flexibility to alter plans of attack, with all ground station personnel performing as a team to quickly take up a different plan during a spacecraft maintenance mission. The design was made with these thoughts in mind. Figure 5-14 illustrates the ground station interfaces. A tie-in to a target satellite data bank provides immediate access to design details of the target satellite. A tie-in to the tracking facilities provides real time ephemeris data of both remote manipulator spacecraft and target satellite. A tie-in to the target satellite control station provides immediate accessibility to target satellite status. Finally, communications services are provided through a tie-in to synchronous data relay satellite facility.

The ground station is trailer mounted in order to allow repositioning for each mission. A plan view of the trailer layout is shown in Figure 5-15. The trailer is manned by the following personnel:

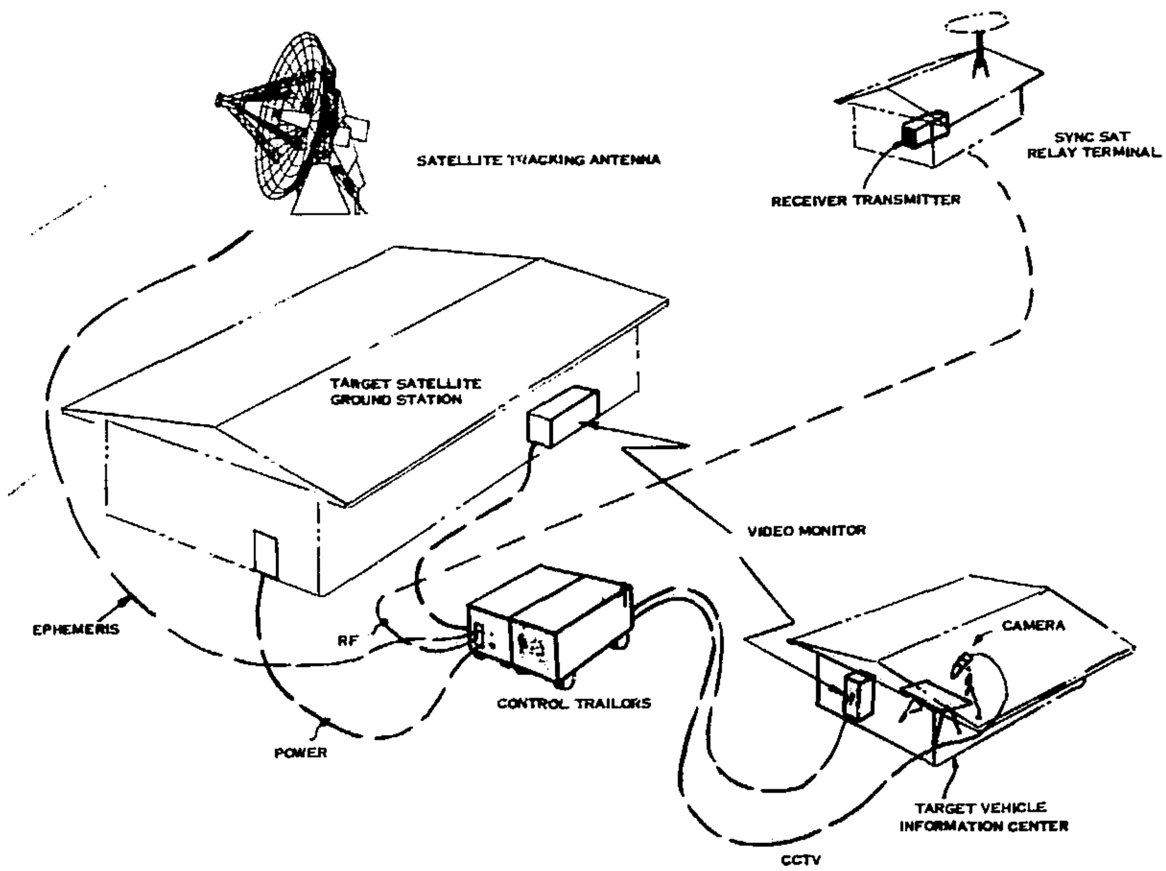


Figure 5-14. Ground Station Interfaces

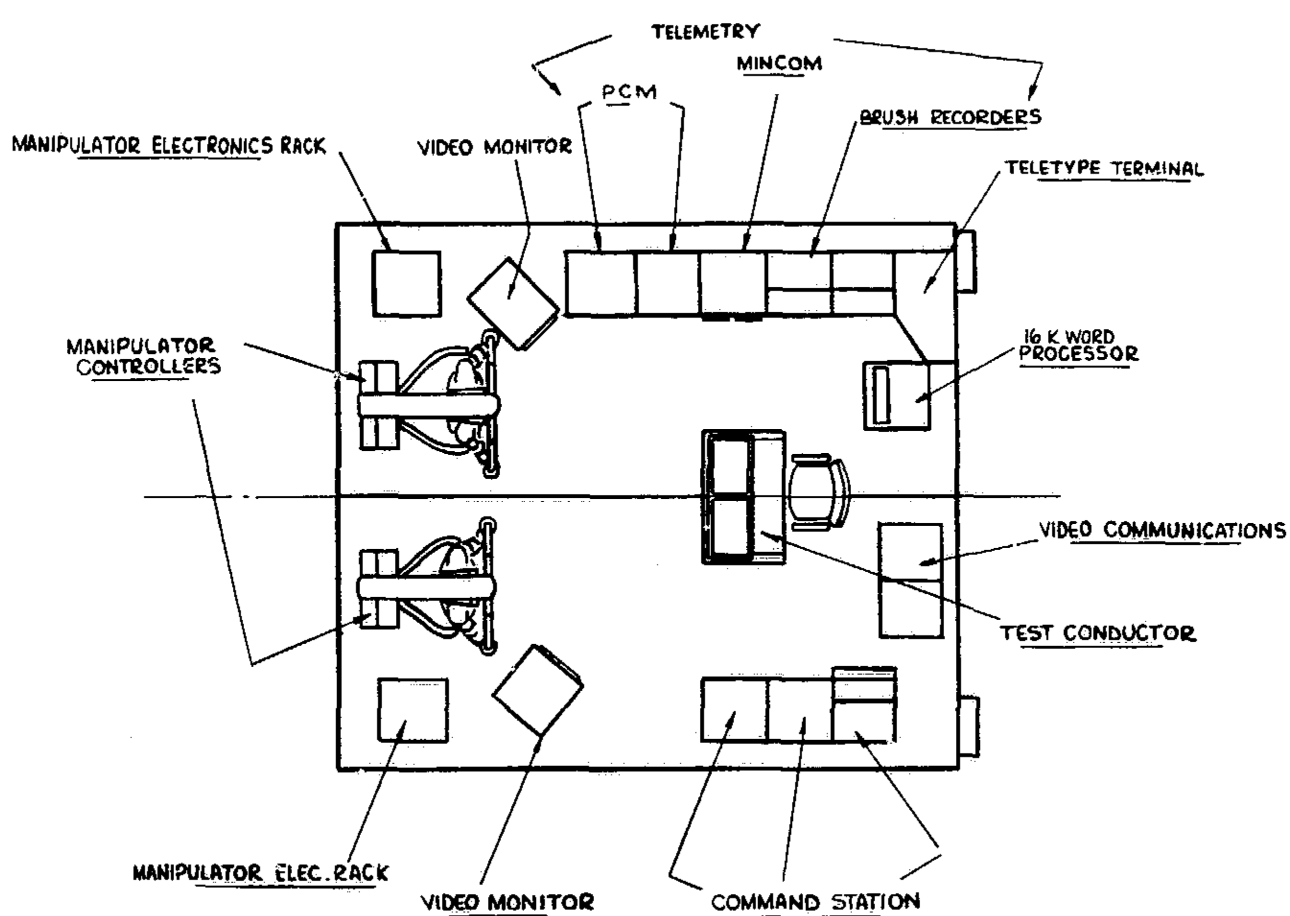


Figure 5-15. Ground Station Layout Plan View

a. Two manipulator operators

b. One test conductor with overall responsibility and authority for the mission.

c. One housekeeping telemetry monitor

d. One communications system operator

e. One target vehicle monitor

A factory ground station to be used during system test is provided. This unit is not van mounted but the equipment is similar to that of the ground station.

5.3 PHASE III - SYSTEM COST ESTIMATE

The costs for the remote manipulator spacecraft system described in Phase II were estimated. Labor rates used were the projected values for 1973. The summary of costs for the manipulator subsystem appear in Table 5-9. These costs are strictly labor and material costs with no adders. These costs were broken out independently because this key subsystem represents a major new technology area and is of significant importance. The development costs include two pair of master manipulators for the ground station and the recurring costs include one pair of slave manipulators for each spacecraft.

Table 5-9. Manipulator Subsystem Costs

Phase	Cost ($K)
Development	2017.8
First Pair of Flight Arms	142.3
Five Additional Pair of Flight Arms	132.5 (each)
Twenty Additional Pair of Flight Arms	122.7 (each)

The costs for the complete system appear in Table 5-10. The development costs include an engineering prototype spacecraft, a qualification spacecraft, ground station, AGE, special test equipment, simulation and training. The recurring costs are the costs for the first

Table 5-10. Remote Manipulator Spacecraft System Cost Estimate

	Development	First Flight Unit	Total
Hours:			
Engineers	203,108	52,176	255,284
Draftsmen	59,488	2,288	61,776
Hourly	81,536	28,496	110,032
Technicians	191,168	51,384	242,552
Total Hours	535,300	134,344	669,644
Dollars:			
Labor:			
Engineers	2,300,794	593,155	2,893,949
Draftsmen	403,329	15,513	418,842
Hourly	373,851	130,431	504,282
Technicians	1,274,166	346,411	1,620,577
Total Labor	4,352,140	1,085,510	5,437,650
Overhead 128%	5,570,739	1,389,452	6,960,192
Material	5,055,100	1,567,400	6,622,500
Subcontract (Manipulators	2,858,000	215,000	3,073,000
Sub Total	$ 17,835,979	$ 4,257,362	$ 22,093,342
CIRP 1.2%	214,032	51,088	265,120
Sub Total	$ 18,050,011	$ 4,308,450	$ 22,358,462
G&A 9.2%	1,660,601	396,377	2,056,979
Total Estimated Cost	$ 19,710,612	$ 4,704,827	$ 24,415,441
Fee	1,576,849	376,386	1,953,235
Total Estimated Cost and Fee	$ 21,287,461	$ 5,081,213	$ 26,368,676
Cost of each of next 10 flight units is estimated to be $ 4,064,970			

flight unit and launch support. Multiple unit costs for the next 10 flight units are shown. The sustaining costs include the cost of ground control station operation and the cost of relay satellite services. The relay satellite service costs are set by the FCC.

The costs are based on the four year development plan of Figure 5-16. The first 20 months are used to finalize the design and begin assembly of mock-ups and of the engineering prototype spacecraft. Fabrication of the qualification vehicle begins at the end of the second year and spacecraft qualification is completed by the middle of the fourth year. The first flight unit fabrication begins at the start of the third year and flight acceptance testing is completed at the end of the fourth year.

Table 5-11. Remote Manipulator Spacecraft System Sustaining Costs

Item	Cost Per Flight ($K)
Relay Satellite Services	$ 218.0
Ground Control Station Operation	43.2
Total	$ 261.2

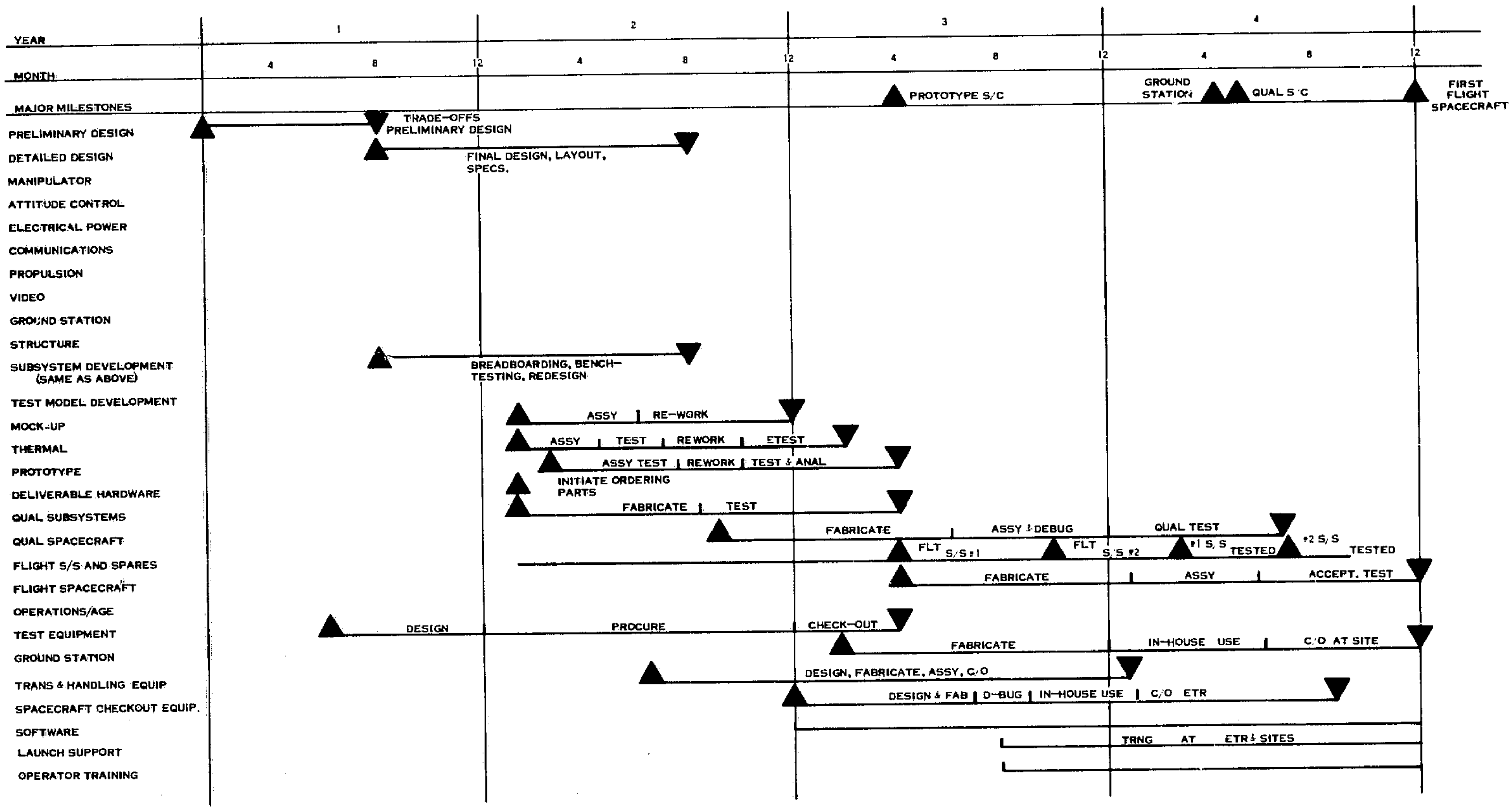


Figure 5-16. System Development Plan

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

The study meets all of the objectives of Section 1.2. The most significant result of the study is the analytical demonstration that a remote manipulator spacecraft system is feasible for on-orbit maintenance operations from a technical viewpoint.

Other important results are:

- For a single mission spacecraft, a 10-day design life is adequate.
- The spacecraft design is achievable with a majority of components that are space qualified.
- The unqualified components used require no technology breakthroughs, only an extension or modification of existing hardware or designs.
- The spacecraft reliability prediction in excess of 0.90 is well above that of satellites being repaired.
- Key maintenance tasks were successfully simulated in the laboratory using remote manipulators and a video display.
- Manipulator requirements for all missions analyzed are similar, suggesting a general purpose design.
- The manipulator performance requirements are very close to man's performance capabilities and hence the manipulators are designed to be man equivalent. This feature makes the system interchangeable with an astronaut in an EV mode.
- The remote manipulator spacecraft costs are, in general, well below the costs of the complex satellites it would service.
- The spacecraft was designed for launch on small, low-cost boosters. These launch vehicles, in general, are smaller and cost less than those used to launch complex satellites to be serviced.

Several problem areas which required additional investigation are also identified in the study. These are:

a. Docking with uncooperative tumbling satellites requires further analysis. As was previously mentioned, docking with OAO would not be attempted if it were tumbling with a rate in excess of 1.5 rpm. However, OAO was a very rigid vehicle with an equal inertia distribution. Docking with vehicles having different inertial distribution and rigidity was not examined in detail.

b. The single remote manipulator spacecraft approach (Figure 2-1a) presents several problems. The first is the ability to maintain continuous communications. A second problem is that of flight vehicle qualification.

   For low orbit missions, the spacecraft must track a synchronous data relay satellite with an articulated, high-gain antenna. During the docking maneuver, track could easily be lost. During the working periods, high gain communications are lost for a brief period four times during each orbit as the antenna is slewed from relay satellite to relay satellite. Again track could be lost. The spacecraft is equipped with a backup omni-antenna but situations are possible in which both modes could be lost. A dual spacecraft concept could overcome this difficulty by shifting the burden of tracking the relay satellite or ground station to the second vehicle called a tender. The tender, furthermore, could use a phased array as the high-gain antenna to avoid loss of tracking when slewing between relay satellites. Beam splitting would be employed for those situations. The phased array also eliminates attitude control disturbances which result from an articulated antenna. The single vehicle system could not use a phased array antenna because of the limits of beam steering.

For each mission, the remote manipulator spacecraft must carry up all cargo and tools. The final launch configuration will vary for each mission because of the differences in cargo and tools. This might require qualification tests on every complete configuration prior to launch, which adds time and money.

Although some problem areas exist, the results of the study encourage further effort in the development of a remote manipulator spacecraft system. A remote manipulator spacecraft system could well be developed and flight tested from a manned space station to establish operational feasibility. Similar systems could eventually be developed and deployed to perform lunar and planetary exploration.

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